Center for Advanced Computation

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CAC Document No. 183

IMPROVED EFFICIENCY OF TOTAL ENERGY SYSTEMS THROUGH WASTE HEAT ENERGY UTILIZATION

by

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ABSTRACT

Increased efficiency of power systems is investigated with considerations for economic, mathematical and engineering feasibility. In particular, a study comparing two alternative modes of energy output for a nuclear power plant is discussed with conclusions and comments as to maximum theoretical efficiency and optimal operating conditions. Discussion of several current methods for improving idle plant capacity and optimal consumer demands is included.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGMENT

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Extra thanks go to Mrs. Veronica Soltys for her efforts in the organization and publication of this thesis.

1.0 INTRODUCTION

This project investigates the possibility of increased efficiency for power plants through the use of waste heat created within the system. By using a dual output system, as opposed to the more conventional single output electrical network, it is theoretically possible to convert some of this waste heat to useful purposes. Limits to this problem are set by the maximum work output possible under the first law of thermodynamics and the engineering feasibility of such a plant [1]. Practical limitations on steam pressures, temperatures, environmental and cost considerations are but a few of the many factors which should be analyzed for a complete study of a project of this size. To eliminate many of these problems, while trying to remain as close to reality as possible in our models, this study has attempted to simulate many of the design features of power plants already in existence or proposed. Any simplifying assumptions made are duly noted within.

To determine the comparative efficiencies of both systems, two mathematical models were created representing all internal cycles in the power plant from material gathered from GE and the reactor division of Oak Ridge Laboratories [2, 3]. These models were programmed on an IBM 360 for mass calculation of dynamic load points. Results from these programs reveal the true system efficiency at all operating times for fluctuating seasonal and daily demands.

Our definition of efficiency here is an operational one defined by taking the total useable Btu's or MW's delivered divided by the total energy created by the reactor.

The problem of fluctuating daily loads is also taken under consideration to improve the use of idle capacity within the power plant as much as possible. This helps provide for maximum utilization of potential power within the system since standby capacity represents a significant cost to utilities today.

It is hoped that the conclusions and alternatives arrived at within this study may provide some insight into the many environmental and energy connected problems generated by our power systems today. It is well known that these plants are one of the major causes of thermal pollution. With our constant demand for electric power rising each year it has become increasingly important that a solution to the amount of waste heat generated by alleviated. The environmental and efficiency problems are thus directly linked, with increased waste heat utilization offering a prime method for partial solution to these problems.

2.0 EFFICIENCY

The study of efficiency evolves around the First Law of Thermodynamics which claims that, due to increased entropy, one cannot convert all generated energy into useful work. This is caused by the constant degrading of energy within the system to higher entropy, lower quality heat. The work output divided by the heat input gives the theoretical efficiency for our system [1].

The efficiency equation for conversion of energy to mechanical work is:

$$\frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1}$$

where T_1 represents the absolute temperature of the initial hot reservoir and T_2 the absolute temperature of the condensed cold reservoir [4]. For the PWR plant modeled in this study, typical warrented thermal properties list T_1 at about 590°F or 583°K for a 2439 MW reactor and 90°F or 305°K for T_2, the condensed water temperature. This gives a theoretical efficiency value of 47.6%. This figure would be applicable for a single output conventional nuclear electric generating station [2]. Once the system has been altered for dual purpose outputs, our operational definition is used to describe the additional use of steam since the Carnot cycle definition is not applicable. The value 47.6% may be used as an indication for comparison between the actual operating efficiency of the single output plant and its theoretical limits. Further limitations on the dual output system arise only from the fact that the

entropy of the cycle attains such a high level that mechanical work or useful transference of energy becomes impractical for conventional uses of heating, air conditioning and electrical generation [5].

Some preliminary studies involving the dual generation of steam and electricity suggest that the practical limitations for this system may appear to be around 90%, theoretically. This is a vast improvement over the usual 47.6% limit [3].

3.0 POWER SYSTEM DESCRIPTION AND ASSUMPTIONS

3.1 Reactor Model

The system under study involves modeling a standard GE PWR (pressurized water reactor) with a 100% warranted thermal output of 2439 MWt. This is used in conjunction with an appropriate steam generator or heat exchanger to provide a low radioactive secondary cycle enabling safer steam usage and easier control (Fig. 1)[6]. Operating points were obtained from GE performance data and used to construct a straight line segment model for the reactor turbine combination (Table 1) [2].

3.2 Turbine Model

A GE model TC4F-38 turbine was matched to the PWR reactor to give a maximum electrical output of 837.8 MWe at 2439 MWt reactor output. Operational assumptions made on the system include 100% moisture separation, constant losses due to components outside the turbine-condenser region, full throttling method of steam control and minor fluctuations in efficiency due to slight variance in turbine back pressure. The maximum error in output power due to small differences in back pressure using 2 inches Hg as a standard was +1.8% and -2.2% at 1220 MWt. All operating levels below 50% of the warranted thermal capacity were extrapolated from the last operating segment given in the turbine data. Plotting of the data in Table 1 indicates only slight variation from linear performance down to 50% thermal capacity. Multiple preheat stages are used at all temperatures to preheat the outgoing secondary condensed water flow to 420°F before return to the steam generator. A three segment turbine is used to drive the generator which will supply power to the fluctuating load [2].

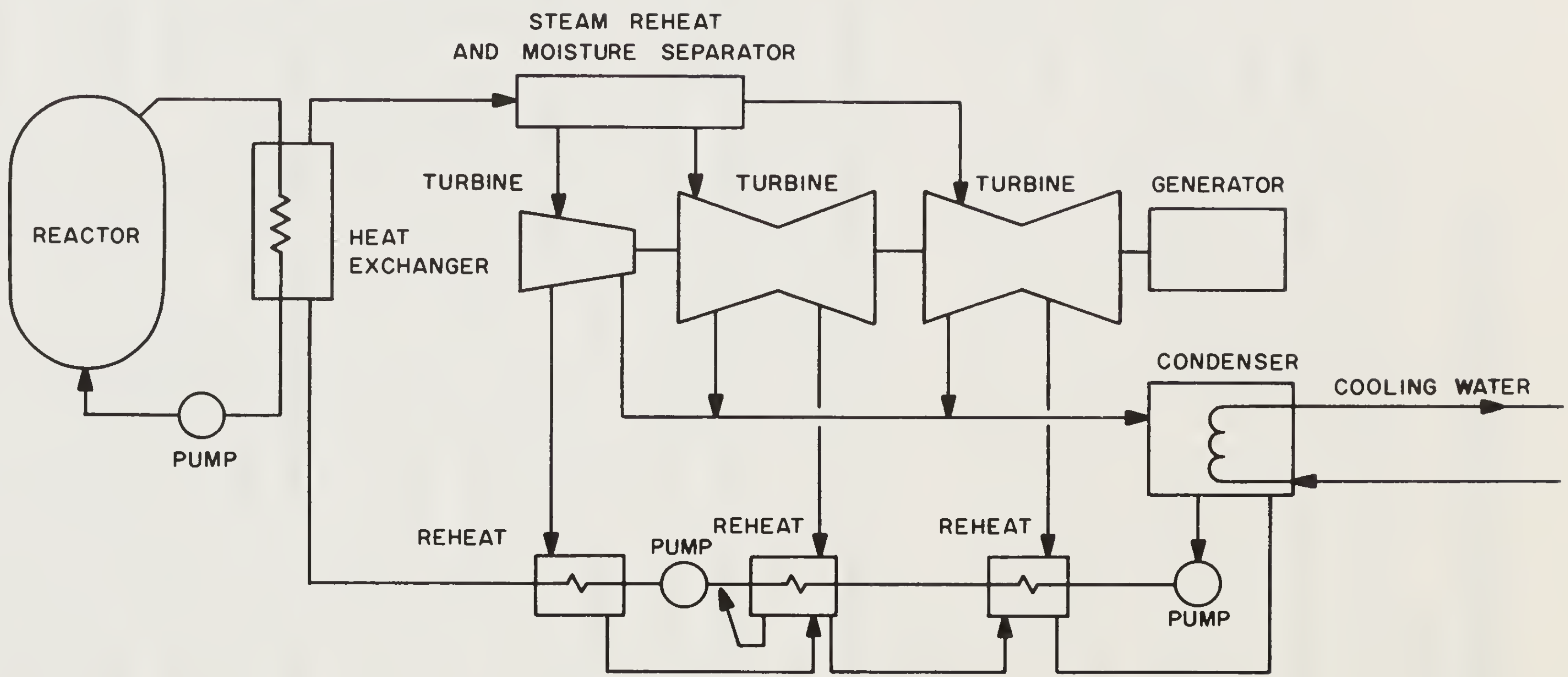

FIGURE I. PWR TURBINE-REACTOR SYSTEM

TABLE 1. Heat Rates for Turbine Generators Applied with GE Standard PWR

Warranted thermal output = 2439100 KW

Final feedwater temperature at warranty = 420°F

Condensate storage tank flow = 30000 lbs/hr.

TC4F-38 2 stage reheat cycle - Output in MW

Final Exhaust Pressure	Percent of reactor warranted thermal output			
	100	88	75	50
1.5	838.3	742.3	626.6	399.1
2.0	837.8	741.0	623.8	391.9
2.5	835.6	740.0	618.6	383.2

3.3 Modified Steam Extraction Turbine Design

Fig. 2 shows the schematic design for the modified proposed turbine system for steam extraction. GE provides many turbines equipped for automatic extraction at all temperatures and a variety of capacities [7]. This steam, taken at a temperature slightly higher than 400°F would flow through heat exchangers to reheat the district heating supply steam to 300°F. Data for a typical steam extraction system was provided by the reactor division of Oak Ridge Laboratories [3]. Performance for the combined electric-steam system may be calculated directly through the use of steam tables and evaluation methods for industrial power plants [7]. For this study, the data given by Oak Ridge was deemed sufficient for drawing initial conclusions on the system design.

This steam at 300°F would then be pumped from the source generating station by means similar to those in use for steam today and used for absorption air conditioning of homes and commercial buildings during the summer and space heating in the winter [8]. A more detailed description of this system appears in Section 4.2.

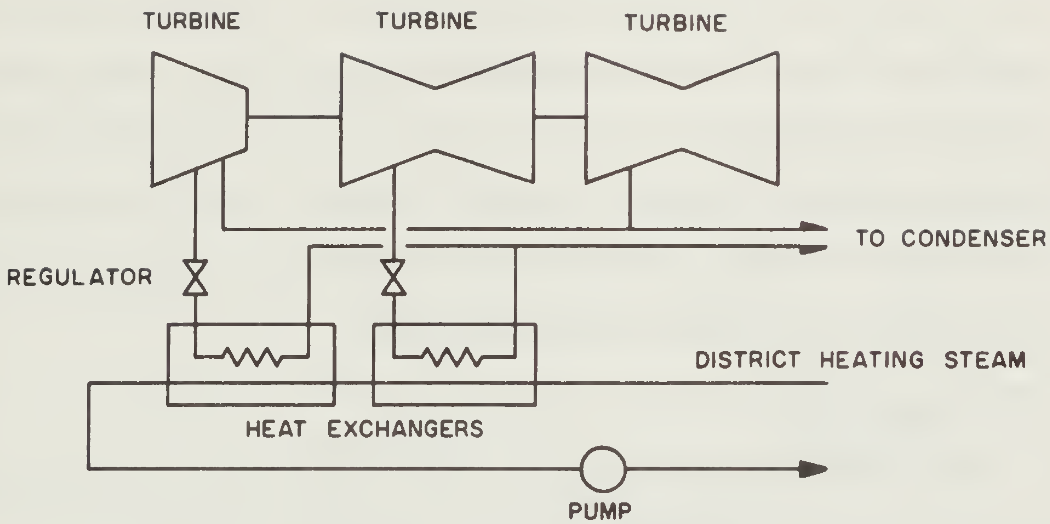

FIGURE 2. MODIFIED STEAM EXTRACTION HEAT PROCESSOR

4.0 EXECUTION OF PROJECT ANALYSIS

4.1 Statement of Problem and Objectives

We seek a method of comparison for our two alternative output modes of power production (with processed steam output and without) to determine which, when applied to a typical dynamic load, will yield the highest efficiency in terms of actual utilized power. The data given by GE and Oak Ridge provides the basis for evaluating both power sources along all feasible operating points [2,3]. By comparing the amount of utilized MW's for both steam and electric consumption, we will be able to determine under what conditions each system is the most efficient in addition to comparing both systems under similar operating modes.

4.2 Methodology

The efficiency calculations for mass data points were carried out by the two computer programs listed in Appendices A and B.

For calculation of the single output electrical efficiency, a simple program utilizing the straight line segment input-output data for the reactor was formulated. For this study, zero loss due to transmissions between source and load was assumed. Therefore, the demand applied to the source was matched directly by the source output in MWe. Three line segments were used to describe the complete operating conditions for the source. Data is read in off the card reader in MWe as electrical demands by consumers for a given time interval. The data is matched with a corresponding reactor output in MWt which is used as the basis for system input power. Efficiency is then calculated by taking the consumer demands divided by the reactor output power. Each of these parameters is listed in the printout as seen in Appendix A.

The dual load calculation becomes more involved as we attempted to match each load characteristic with the appropriate source output while trying to maintain a minimum reactor operating level. To achieve this, system data utilizing the modified extraction turbine network described previously was used for locating the appropriate reactor output level proportional to the steam utilized and electrical demand. Maximum electrical output from the source was set at 837.8 MWe. In our calculations, peak demands for electricity did not exceed 837 MWe. Data on the electric and steam load demands are read in initially as seen in Appendix B. Excessive demand for electricity is then checked. Corresponding heat load is then calculated from the utilized steam demand read in. This takes into account all transmission steam losses from turbine extraction to residential delivery. Once the heat load factor is determined, steam generator energy may be calculated in utilizing both the heat load and the current electrical demand. This calculation determines the reactor power output needed to supply the desired amount of extraction steam while still allowing the turbine to produce the desired amount of electrical output. A plot of this function reveals the percentage loss in generating ability as larger quantities of steam are extracted (Fig. 3) [3].

Efficiency of the system is calculated by combining the utilized steam and electric loads read in, divided by the steam energy generated or the reactor output power. Each of these operating factors is listed in the program output along with the corresponding demands shown in Appendix B. This program automatically adjusts the source's output to the particular demands with the minimum reactor output level.

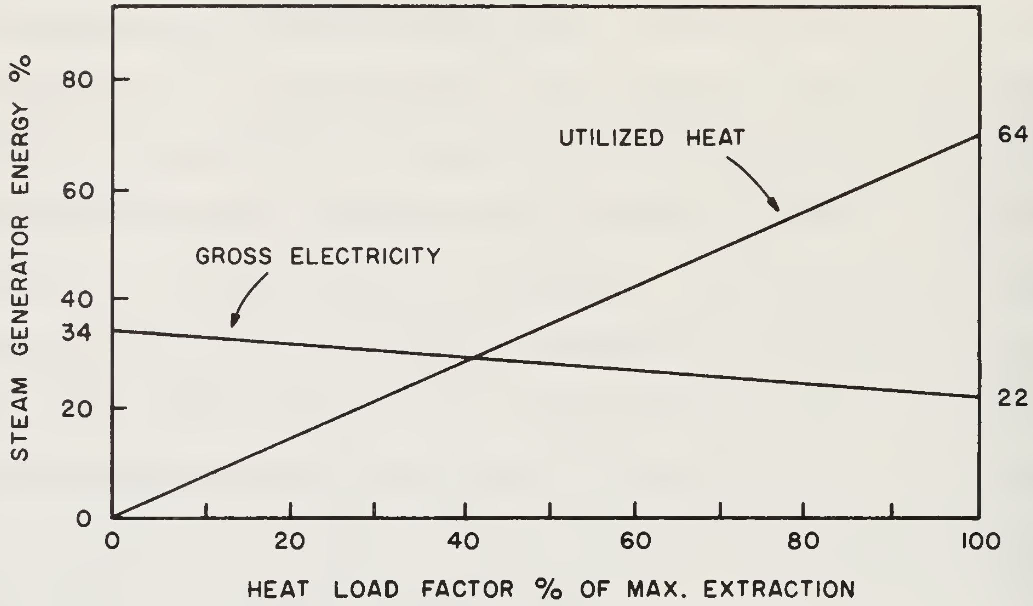

FIGURE 3. POWER PRODUCTION AS A FUNCTION OF HEAT LOAD FACTOR

Once these programs were developed, an appropriate test region used at Oak Ridge Laboratories was selected for analysis with the two alternative power systems. The reference city chosen contains a population of approximately 400,000 with a geographical climate similar to Philadelphia. This provides ample opportunity for space heat and absorption air conditioning utilization. Limits on transmission distance were placed at 15 miles for both electric and steam loads. Maximum electrical transmission loss at this distance is estimated to be less than 5% [9]. Statistics for seasonal and daily load factors for such a city were provided from a study by Oak Ridge [10]. The steam system in use is assumed to have regional pumping and regulatory stations throughout

the city, extracting the necessary amount of steam from the main and distributing it evenly over specified districts. Hot water vapor is returned by a similar system to the source for reheating.

Seasonal variations in consumer demands for the city's steam and electric consumption for a current typical year are listed in Table 2. These loads are projected averages taken from readings made during 1967 with adjustments made at Oak Ridge for absorption air conditioning and additional district steam loads [11]. Of greater importance are the daily fluctuations in consumer demands listed in Tables 3 and 4. These reflect a piecewise representation of hourly changes in demand for two dates as registered by the city's power company. These loads are assumed to be the result of typical residential-commercial consumer needs in the city with decentralized absorption air conditioning units and standard hot water heating in each of the housing units and stores.

TABLE 2. Seasonal Consumer Demands

MONTH	CONSUMER STEAM DEMAND MWt	CONSUMER ELECTRIC DEMAND MWe
January	500	480
February	505	480
March	520	480
April	520	480
May	370	425
June	430	430
July	460	430
August	450	430
September	420	430
October	360	440
November	408	480
December	430	480

TABLE 3. August 10 Consumer Demands

	TIME	CONSUMER STEAM DEMAND MWt	CONSUMER ELECTRIC DEMAND MWe
	12	330	344
	2	330	275
	4	350	258
A.M.	6	430	267
	8	540	378
	10	550	525
	12	555	559
	2	550	559
	4	540	550
P.M.	6	440	512
	8	370	469
	10	350	469

TABLE 4. December 7 Consumer Demands.

	TIME	CONSUMER STEAM DEMAND MWt	CONSUMER ELECTRIC DEMAND MWe
	12	420	384
	2	425	307
	4	430	283
A.M.	6	490	288
	8	580	398
	10	590	566
	12	570	614
	2	550	614
	4	530	600
P.M.	6	480	562
	8	425	494
	10	410	494

5.0 CONCLUSIONS AND RESULTS

Computer output for each set of data appears graphically in Figures 4, 5 and 6. It is apparent that seasonal and daily variations in operation mode for the single output plant barely affects its overall efficiency rating. The major drawback in this system, however, is its inability to attain an operational efficiency of greater than 35%. This indicates that a great deal of initial generated power is being lost or dumped within the system, even though its maximum theoretical efficiency is somewhere in the neighborhood of 47.6%. This difference of 12.6% represents a loss of 307 MW's due to inefficient heat transfers, pipe losses, and other non-theoretical sections in the system. Another drawback discovered while testing the program was the sharp decrease in single output system efficiency when operating at levels of 50% or less of the warranted thermal capacity. The entire turbine cycle efficiency slumped to 25% from 33% when operating near half capacity. This was probably due to the designed operating conditions of the turbine when used at low power.

The major result obtained through this study reveals that the use of a dual purpose power plant provides significant improvement in energy efficiency when compared to the conventional system. Despite seasonal and daily fluctuations, the dual output system maintained at least a 52% improvement in efficiency over the single output system.

The seasonal variation chart, Fig. 4, shows two areas of reduced efficiency during May and October, which could be expected since these are the two periods of reduced steam and electric demand shown in Table 2.

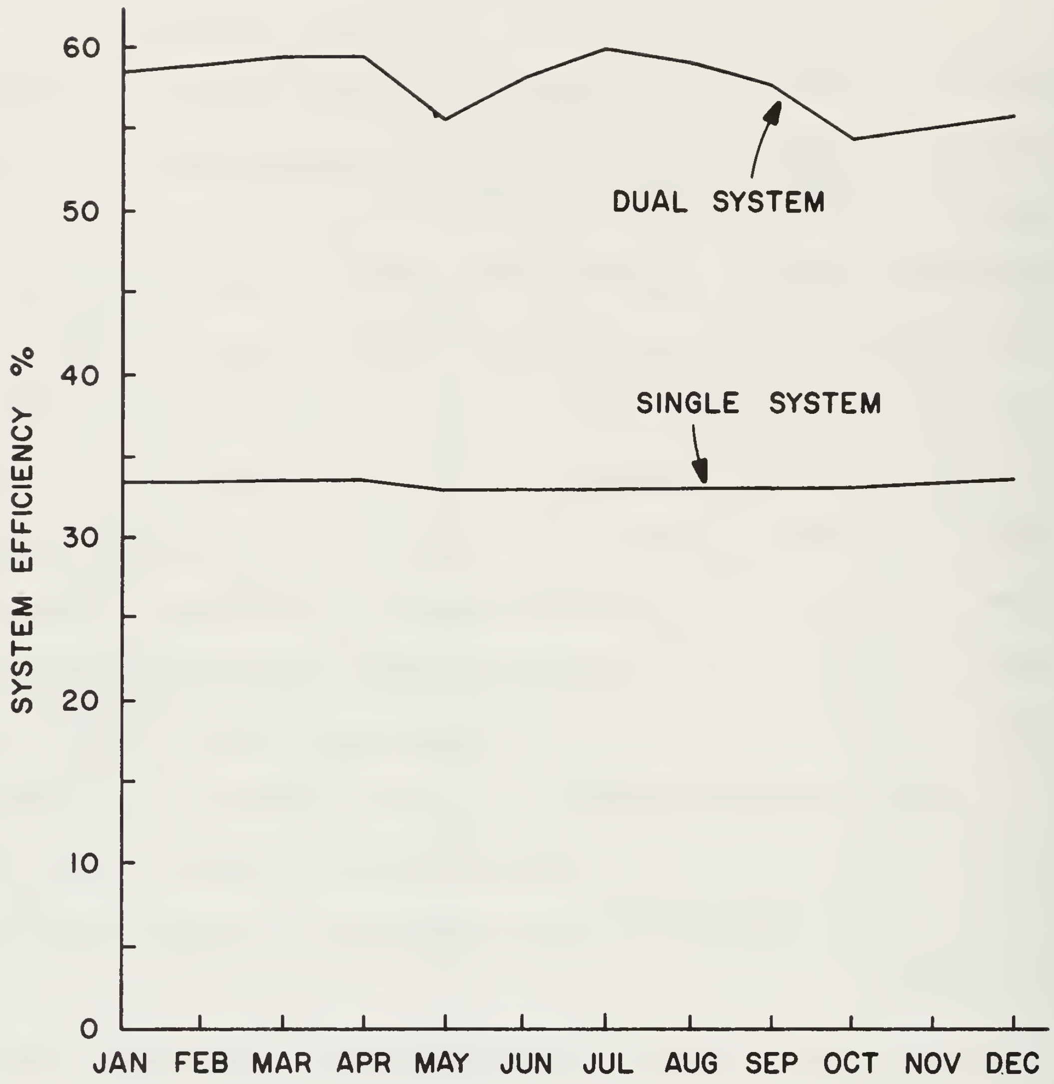

FIGURE 4. SEASONAL VARIATION COMPARISON BETWEEN DUAL AND SINGLE FUNCTION PLANTS

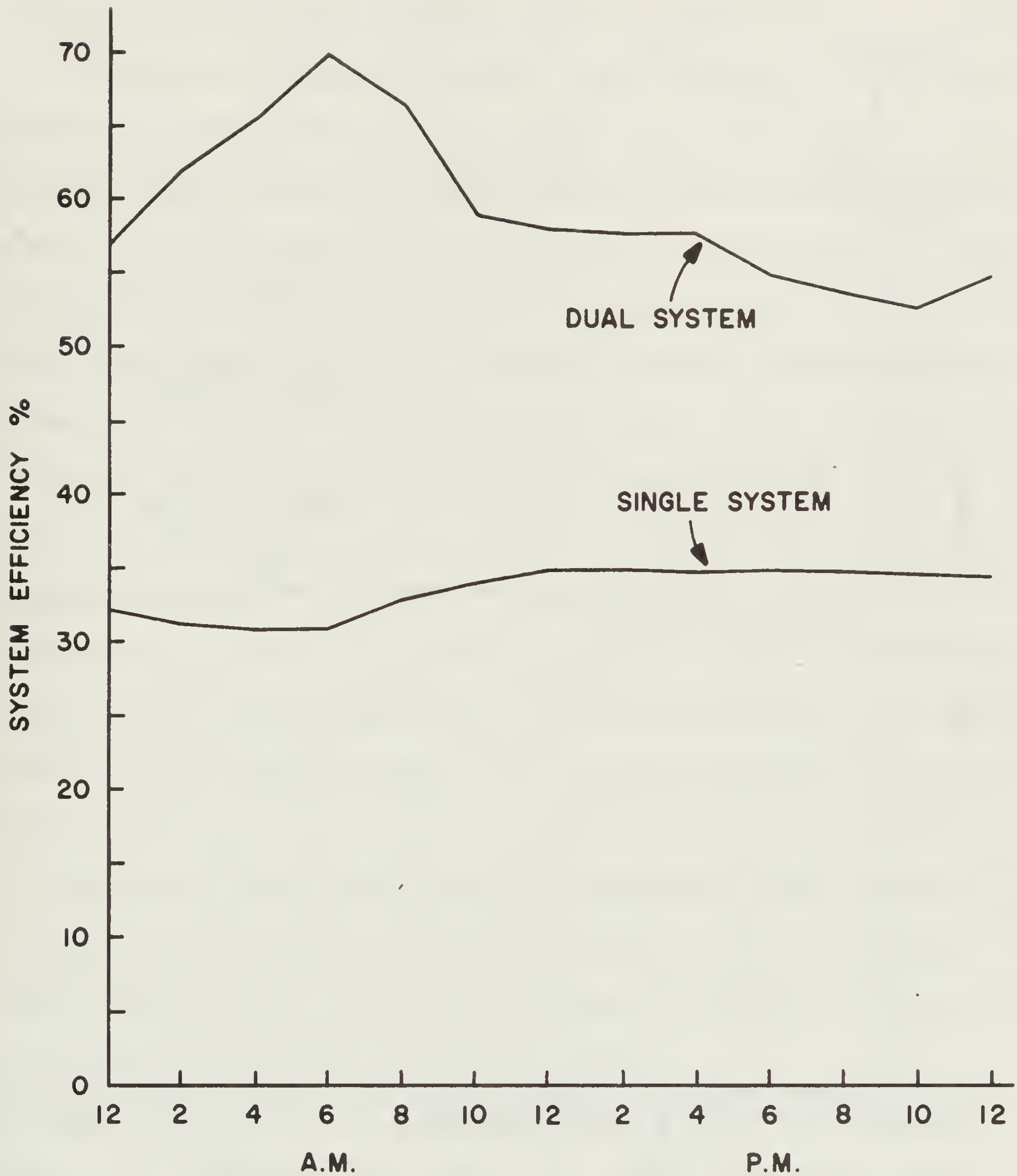

FIGURE 5. HOURLY VARIATION IN EFFICIENCY ON AUG. 10 FOR DUAL AND SINGLE FUNCTION PLANTS

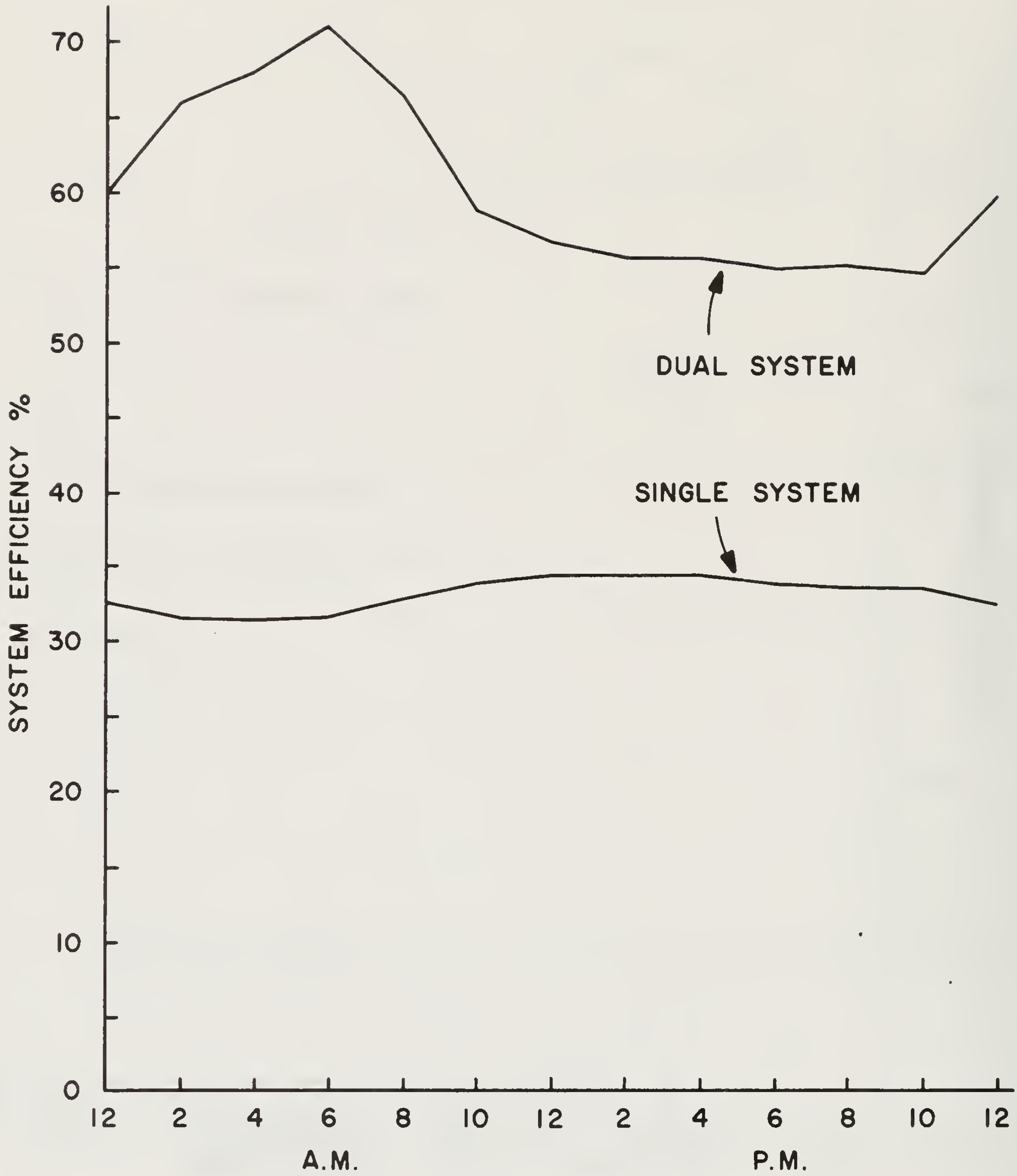

FIGURE 6. HOURLY VARIATION IN EFFICIENCY ON DEC. 7 FOR DUAL AND SINGLE FUNCTION PLANTS

Such fluctuations in the dual output system are a result of the efficiency of the steam extraction and heat transfer process.

Examination of Fig. 5, the daily efficiency chart for August 10, reveals even wider fluctuations. As shown previously in Fig. 3, this system becomes extremely efficient as more steam is extracted from the turbine cycle, up to the maximum allowable for minimal electric generation. This study found the early morning hours to be those of greatest system efficiency. This was due primarily because of moderate steam demands and lower electric output. Many people may be running their air conditioners at almost constant levels from the hours of 11 P.M. to 6 A.M. This, coupled with a possible drop in electric usage from lighting and appliances after 12 P.M. could provide the necessary characteristics needed for improved efficiency. Higher steam demands during mid-hours with equally high electric demands forced the generating plant to full capacity but with reduced overall efficiency. Sustained high electric usage into the early evening hours with a gradual slump in steam demand due to lower ambient temperatures caused a further drop in the efficiency as the demand curve approached one similar to the single output system. Significant improvement in system performance is maintained throughout this period, however.

Fig. 6 shows the corresponding efficiency curve for a typical winter day, December 7. The curve is similar in form to the summer one with shifts occurring during the early morning hours and through the afternoon. Steam usage appears to maintain a much more even demand, since the majority of this is used for home heating (Table 4). The peak levels for steam are slightly higher than during the summer but

evening levels are significantly higher due to space heating during periods of low temperatures. The electric demands seem elevated from summer levels but with much the same proportions. Together these two demands create a slightly lower system efficiencies during the hours of 7 P.M. to 10 A.M. and increasing efficiency during 11 A.M. to 6 P.M. when compared to the summer graph.

Additional consideration in evaluating coal-fired generating plants as compared to nuclear systems should take into account energy loss due to chimney heat and the heat exchange process. Conventional fossil-fuel plants release approximately 15 to 20 percent of their total boiler heat into the atmosphere during steam generation while 5 to 10 percent of the total energy in a PWR nuclear steam cycle is lost in steam generation through heat exchangers [4]. By using the proposed system of steam for residential use, an additional 5 to 10 percent loss is incurred within the system by using the extra steam generation for the district heating supply. A comparison of total generating power between the PWR v. fossil-fuel plants reveals a 10 percent improvement in cycle efficiency for the conventional fossil-fuel system, due primarily to the use of higher steam temperatures and pressures within the system enabling more efficient heat-energy transfers. Because of the high risks involved in using high pressure systems in nuclear plants, conventional coal-fired systems are currently able to operate more efficiently in generating electric power [4]. Direct steam extraction for the district heating supply in the conventional system will also improve total efficiency by eliminating the lossy heat exchanger used for isolation purposes in the nuclear system.

Another item to be considered in such a residential heating system is the possible risk to the population from accidental exposure to radioactive effluents. Studies utilizing statistical and probabalistic techniques indicate that the possible mortality risk factor associated with a nuclear as opposed to a coal-fired accident are at least an order of magnitude larger for typical plant malfunctions or release of operational pollutants to the air at the plant site [12]. An additional risk factor may exist if such a nuclear accident should somehow cause radioactive particles to be transmitted in such quantity as to deliver harmful doses of radiation through the district heating supply to the residential sector. Although the use of a third enclosed steam system reduces this probability to a minimum, daily low level doses and the existence of the threat of nuclear accident and exposure must be taken into consideration in evaluating such a project. Use of a coal-fired generating plant could eliminate this additional high risk.

It should also be noted that these results have not been cost adjusted, since this study covers an engineering as opposed to an economic analysis of power plants. Recent investigations have found that fuel and fuel cycle costs associated with nuclear power plants have risen to considerable levels in recent years making the use of nuclear as opposed to coal fueled plants highly questionable. In addition to these fuel costs are the large capital requirements needed to fund nuclear power systems, all of considerable importance in evaluating proposed power plants [13].

With increased energy utilization within the power plant, a vast decrease in the amount of waste heat results. This means less condensor water being dumped into lakes and streams, much less. While not completely eliminating the problem of thermal pollution from waste heat, this report shows that the amount which must be eliminated can be cut by as much as 56%. Although a city supplied by an electric-steam system may require large alterations in the current system or considerable planning for a new city, the possible savings in efficiency and environmental protection make this plan well worth considering. About fifty large power stations currently supply both electricity and steam for residential and commercial use, the largest being Consolidated Edison's New York plant which supplies Manhattan [5]. Although these are of the coal burning type, a new dual reactor under construction in Midland, Michigan, will possess the potential for delivering 1380 MWe for consumer use and large amounts of processed steam to the Dow Chemical Company by steam extraction for industrial use [14].

6.0 NOTES ON IMPROVEMENT IN PLANT IDLE CAPACITY

Due to the uneven dynamic power demands of consumers, constant feedback is necessary within the system to detect these fluctuations and provide the necessary changes in generation capacity. A majority of power plants are designed to operate most efficiently in the region near maximum capacity. At numerous periods where less than maximum generation is required, efficiency is lost within the system. Because of this, it would be much to everyone's advantage to seek out a method whereby the load curves would become essentially constant. This would allow our power plants to be designed over a very narrow, highly efficient operating region.

Upon consideration of this problem and by comparing the results in Section 5.0, we see that the evening period to early morning is one of decreased electrical demand. If this curve could be shifted evenly by dropping peak demand periods with a minimal raising of the slumps, it would be ideal.

Several methods now under consideration or in current use for coping with this problem and encouraging energy conservation are, adjustments in the utility rate structures, promotional advertisement, and methods for storing potential energy during periods of low consumer demand.

Many state utility commissions have enacted or are studying the possibility of flattening current rate structures to discourage excessive power use formerly encouraged by offering lower rates for greater consumption. This usually involves the use of differential peak load pricing for daily and seasonal demands, and marginal cost

pricing, as opposed to the more conventional average cost pricing. The commissions feel that by flattening residential, commercial, and industrial rate structures, charging flat rates for excess power levels and using differential pricing, additional electrical energy conservation can be achieved which may help with the peak loading problem. [15]

Since the energy shortage, utilities have boosted the number of promotional ads for energy conservation, although the net effect of these on lowering peak demands appears controversial at this time. The aim of these ads is supposedly to make people more energy conscious and, therefore, encourage better energy conservation. It can be debated whether or not these ads have done more to promote the utility's institutional image as opposed to helping ease the peak demand problem [16].

Many research groups, including the Electrical Power Research Institute, Oak Ridge Laboratories, and a number of university research teams, are currently investigating numberous methods for storing vast amounts of potential energy during off-peak load times to help even out the demand curve for electrical power plants. Pumped storage of water at hydroelectric power plants into reservoirs is already in use at several sites across the nation [9]. Magnetic field storage of potential energy in large superconducting inductors and low friction magnetic bearing flywheels appear to offer an efficient method for mass energy storage at a possible efficiency of ninety-five percent. Other options including compressed air storage and molten galbers salt heat energy are being investigated and have thus far shown promising results on small scale tests. These methods have yet to be installed on a wide scale at existing power plants, but may one day provide an

answer to the fluctuating load problem [17].

These characteristics of uneven demands and idle plant capacities have existed for decades and appear may continue until such time as technology allows for the creation of a power plant capable of efficient power generation along all operating levels, or an efficient, practical storage device is found able to handle the excess power demands created by our fluctuating load factors.

7.0 CALCULATION OF OPTIMAL OPERATING POINT FOR THE DUAL OUTPUT SYSTEM

Given our system of two variable outputs, we would like to come to some conclusion as to an optimal operating point, taking into account energy costs and profits. An optimal mix of processed steam and electric output may be calculated utilizing joint products theory. This method will combine a plot of the power plant's possible operating points with a family of curves defined by the energy costs of each point and the revenue generated by each operating point [18]. By minimizing energy costs and maximizing profits, two optimal operating points will result, which should coincide if utilities are actually striving for maximum energy efficiency with maximum profits.

Fig. 7 reveals the locus of points for our model plant if maximum power generation is considered. Revenue maximization will be calculated first. The joint products equation defining profit in terms of the output quantities is:

$$R = p_e q_e + p_s q_s$$

Where R is the total revenue as a function of the quantities of steam and electricity delivered for customer use, q_s and q_e, and the price charged per quantity of steam and electricity, p_s and p_e. To maximize profit, we take the derivative of the revenue equation and set it equal to zero. This gives:

$$dR = p_e dq_e + p_s dq_s = 0$$

$$\frac{-p_s}{p_e} = \frac{dq_e}{dq_s}$$

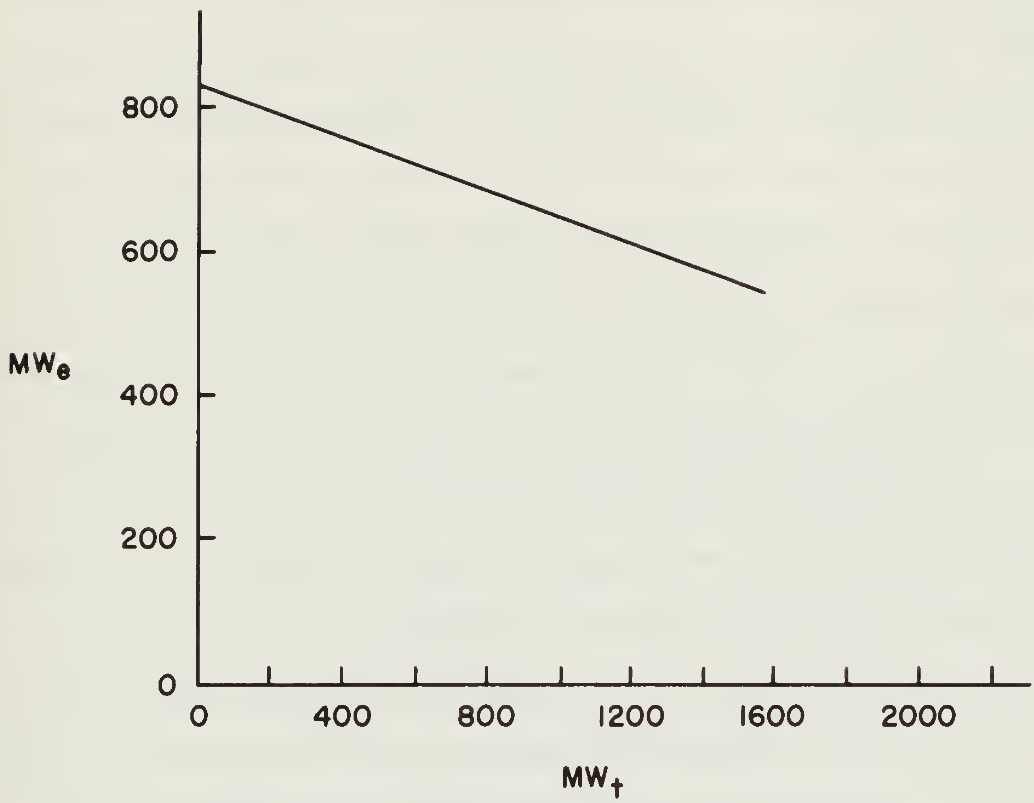

FIGURE 7. OUTPUT LOCUS OF POWER PLANT OPERATING POINTS

The ratio of dq_e/dq_s defines the slope of all possible revenue curves which when placed on Fig. 7 determines for any fixed prices where the maximum revenue intersection will be with our operating line. The critical slope is determined by the operating line which, for our example, is equal to -.188. To maximize profits, we find that $-p_s/p_e$ must be less than the critical slope if all steam is to be produced and greater than the critical slope if all electricity is to be produced. This is due to the linear operating line which we are using which causes the solution point to lie at one of the two end points on the line, and the maximum profit being the largest solution satisfying the revenue equation at a point coincident to the operating line. As an example, if the average price of electricity is chosen to be $.0277/KWe and the average price of steam to be $.00584/KWt, the slope of the corresponding revenue lines would be -.21 [19]. This indicates the utilities should be producing as much steam as allowable under technical limitations to maximize profits. If the price of steam is $.0032/KWt and electricity stays the same, -.116 is the revenue slope which says that maximum profit is attained by producing only electricity.

Energy costs are computed in a similar fashion by using an energy cost equation:

$$E = c_s q_s + c_e q_e + b$$

and comparing to the same operation load line. Slope conditions to minimize energy costs will be directly opposite those for maximizing revenues. If $-c_s/c_e$ is less than the critical slope, all electricity

should be produced. If $-c_s/c_e$ is greater than -.188, maximum steam should be produced. b in the energy cost equation represents the energy cost of capital for the power plant which is taken to be a constant and disappears when we differentiate the equation. To find c_s and c_e in practical given terms, we analyze our system as follows:

E = the total input energy into the system
b = energy cost of capital
Q_s = total steam produced by the steam generator
c_s' = energy cost of Q_s steam
q_s' = quantity of processed steam leaving the plant
E' = energy of the processed steam leaving the plant
q_s'' = quantity of steam used to drive the turbine
E'' = energy of the steam driving the turbine
q_e' = quantity of electricity produced at the generator
E''' = energy of the electricity at the generator
q_s = net quantity of processed steam delivered to the load
q_e = net quantity of electricity delivered to the load
c_e' = energy cost of electricity at the generator

$$E = Q_s + b$$

$$C_s' = E/Q_s$$

$$E' = C_s' \; q_s'$$

$$E'' = C_s' \; q_s''$$

$$C_e' = E''/q_e' = C_s' \; q_s''/q_e'$$

$$E''' = C_e' \; q_e' = c_e' \; E''$$

$c_s q_s = c_s' q_s'$ and $c_e q_e = c_e' q_e'$

$$c_s = \frac{c_s' q_s'}{q_s} \qquad\qquad c_e = \frac{c_e' q_e'}{q_e}$$

$$= \frac{c_s' q_s'' q_e'}{q_e}$$

$$= \frac{c_s' q_s''}{q_e}$$

$$\frac{c_s}{c_e} = \frac{c_s' q_s'}{q_s} \quad \frac{q_e}{c_s' q_s''} = \frac{q_e q_s'}{q_s q_s''}$$

If, using our model power plant, we assume electrical transmission losses of 5% and steam transmission losses of 20%, choose q_s as 1560 MWT and q_e as 537 MWe from our operating line, we get an energy cost slope of -.36. This indicates that maximum electrical energy should be generated for our case to minimize energy costs.

The optimal operating point is entirely dependent on the line losses and the rates charged, which may yield a coincident point, but can be adjusted in this case quite easily to be noncoincident as well.

We realize that our operating line and perhaps our family of energy cost and revenue curves will in reality be of nonlinear functions. This would provide an optimal point other than the end points which would take into account all plant losses and internal system costs. We would like to point out, however, that even with our simplified linear model significant results may be obtained concerning the optimal operating conditions. We found that the prices charged can cause our optimal point to move from one end of the line to the other by only slight variations well within the bounds of current national utility rates [19]. With the line losses and linear approximation of capital energy costs, we also find that the utilities are maximizing energy efficiency if they produce only electricity under our model. With

better data on the actual operating conditions of the power plant and energy costs, exact results could be obtained for any power plant to determine if the utility's goals of revenue maximization are indeed in conjunction or opposition to the energy cost and efficiency of the plant.

Appendix A - Single Plant Output Program

```
$JOB
          PRINT 10
       10 FORMAT(1H1,128('*'),///,41X,'CALCULATION OF SINGLE OUTPUT PLANT EF
         1FICIENCY',///,14X,'CONSUMER DEMAND (MW)',20X,'REACTOR OUTPUT (BTU,
         2S)',19X,'PLANT EFFICIENCY (PER CENT)',///)
C         CONSUMER DEMAND INPUT-IN MW
        6 READ 1,Y
        1 FORMAT(F7.2)
          IF(Y.EQ.0.) GO TO 7
          IF(Y.LE.623.8) GO TO 2
          IF(Y.LE.741.) GO TO 3
          X=(Y-18.46)/.336
          GO TO 4
        2 X=(Y+51.03)/.369
          GO TO 4
        3 X=(Y+43.75)/.365
        4 EFF=Y/X*100.
          X=X*3413.E3
          PRINT 5,Y,X,EFF
        5 FORMAT(20X,F7.2,32X,E10.3,35X,F6.2,/)
          GO TO 6
        7 PRINT 8
        8 FORMAT(1H1)
          STOP
          END

$ENTRY
```

Appendix A (continued)

CALCULATION OF SINGLE OUTPUT PLANT EFFICIENCY

CONSUMER DEMAND (MW)	REACTOR OUTPUT (BTU,S)	PLANT EFFICIENCY (PER CENT)
480.00	0.491E 10	33.35
480.00	0.491E 10	33.35
480.00	0.491E 10	33.35
480.00	0.491E 10	33.35
425.00	0.440E 10	32.94
430.00	0.445E 10	32.99
430.00	0.445E 10	32.99
430.00	0.445E 10	32.99
430.00	0.445E 10	32.99
440.00	0.454E 10	33.07
480.00	0.491E 10	33.35
480.00	0.491E 10	33.35

Appendix A (continued)

CALCULATION OF SINGLE OUTPUT PLANT EFFICIENCY

CONSUMER DEMAND (MW)	REACTOR OUTPUT (BTU,S)	PLANT EFFICIENCY (PER CENT)
384.00	0.402E 10	32.57
307.00	0.331E 10	31.64
283.00	0.309E 10	31.26
288.00	0.314E 10	31.35
398.00	0.415E 10	32.71
566.00	0.571E 10	33.85
614.00	0.615E 10	34.07
614.00	0.615E 10	34.07
600.00	0.602E 10	34.01
562.00	0.567E 10	33.83
494.00	0.504E 10	33.45
494.00	0.504E 10	33.45
344.00	0.365E 10	32.13
275.00	0.302E 10	31.12
258.00	0.286E 10	30.81
267.00	0.294E 10	30.98
378.00	0.397E 10	32.51
525.00	0.533E 10	33.63
559.00	0.564E 10	33.81
559.00	0.564E 10	33.81
550.00	0.556E 10	33.77
512.00	0.521E 10	33.56
469.00	0.481E 10	33.28
469.00	0.481E 10	33.28

Appendix B. Dual Plant Output Program

```
$JOB
      PRINT 10
   10 FORMAT(1H1,128('*'),///,42X,'CALCULATION OF DUAL OUTPUT PLANT EFFI
     1CIENCY',///,5X,'CONSUMER DEMAND (MWT)',5X,'CONSUMER DEMAND (MWE)',
     28X,'REACTOR OUTPUT (MWT)',14X,'SYSTEM EFFICIENCY (PER CENT)',///)
C
C  CONSUMER DEMAND INPUT - IN MWT AND MWE
C
    4 READ 1,E,H
    1 FORMAT(2F7.2)
      IF(E.EQ.0.) GO TO 5
      IF(E.LE.837.8) GO TO 2
      E=837.8
C
C  EFFICIENCY CALCULATION
C
    2 HL=1.4556*H
      SGE=(E+.12*HL)/.34
      EFF=(E+H)/SGE*100.
      PRINT 3,H,E,SGE,EFF
    3 FORMAT(12X,F7.2,18X,F7.2,23X,F7.2,31X,F6.2,/)
      GO TO 4
    5 PRINT 6
    6 FORMAT(1H1)
      STOP
      END

$ENTRY
```

Appendix B (continued)

CALCULATION OF DUAL OUTPUT PLANT EFFICIENCY

CONSUMER DEMAND (MWT)	CONSUMER DEMAND (MWE)	REACTOR OUTPUT (MWT)	SYSTEM EFFICIENCY (PER CENT)
500.00	480.00	1668.64	58.73
505.00	480.00	1671.20	58.94
520.00	480.00	1678.91	59.56
520.00	480.00	1678.91	59.56
370.00	425.00	1440.08	55.21
430.00	430.00	1485.61	57.89
460.00	430.00	1501.03	59.29
450.00	430.00	1495.89	58.83
420.00	430.00	1480.48	57.41
360.00	440.00	1479.06	54.09
408.00	480.00	1621.37	54.77
430.00	480.00	1632.67	55.74

Appendix B (continued)

CALCULATION OF DUAL OUTPUT PLANT EFFICIENCY

CONSUMER DEMAND (MWT)	CONSUMER DEMAND (MWE)	REACTOR OUTPUT (MWT)	SYSTEM EFFICIENCY (PER CENT)
420.00	384.00	1345.18	59.77
425.00	307.00	1121.28	65.28
430.00	283.00	1053.26	67.69
490.00	288.00	1098.79	70.81
580.00	398.00	1468.56	66.60
590.00	566.00	1967.81	58.75
570.00	614.00	2098.71	56.42
550.00	614.00	2088.44	55.74
530.00	600.00	2036.99	55.47
480.00	562.00	1899.54	54.86
425.00	494.00	1671.28	54.99
410.00	494.00	1663.57	54.34
330.00	344.00	1181.30	57.06
330.00	275.00	978.36	61.84
350.00	258.00	938.63	64.78
430.00	267.00	1006.20	69.27
540.00	378.00	1389.18	66.08
550.00	525.00	1826.68	58.85
555.00	559.00	1929.24	57.74
550.00	559.00	1926.68	57.56
540.00	550.00	1895.07	57.52
440.00	512.00	1731.93	54.97
370.00	469.00	1569.50	53.46
350.00	469.00	1559.22	52.53

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